Cropping Systems

Agronomic and Economic Performance Characteristics of Conventional and Low-External-Input Cropping Systems in the Central Corn Belt

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ABSTRACT

We conducted a 9-ha field experiment near Boone, IA, to test the hypothesis that yield, weed suppression, and profit characteristics of low-external-input (LEI) cropping systems can match or exceed those of conventional systems. Over a 4-yr period, we compared a conventionally managed 2-yr rotation system {corn (*Zea mays* L.)/soybean [*Glycine max* (L.) Merr.]} with two LEI systems: a 3-yr corn/soybean/small grain + red clover (*Trifolium pratense* L.) rotation, and a 4-yr corn/soybean/small grain + alfalfa (*Medicago sativa* L.)/alfalfa rotation. Synthetic N fertilizer use was 59 and 74% lower in the 3- and 4-yr systems, respectively, than in the 2-yr system; similarly, herbicide use was reduced 76 and 82% in the 3- and 4-yr systems. Corn and soybean yields were as high or higher in the LEI systems as in the conventional system, and weed biomass in corn and soybean was low (≤4.2 g m^{-2}) in all systems. Experimentally supplemented giant foxtail (*Setaria faberi* Herrm.) seed densities in the surface 20 cm of soil declined in all systems; supplemented velvetleaf (*Abutilon theophrasti* Medik.) seed densities declined in the 2- and 4-yr systems and remained unchanged in the 3-yr system. Without subsidy payments, net returns were highest for the 4-yr system (\$540 ha^{-1} yr^{-1}), lowest for the 3-yr system (\$475 ha^{-1} yr^{-1}), and intermediate for the 2-yr system (\$504 ha^{-1} yr^{-1}). With subsidies, differences among systems in net returns were smaller, as subsidies favored the 2-yr system, but rank order of the systems was maintained.

One of the key questions facing agriculturalists in the 21st century is how to produce adequate amounts of food, feed, and farm income while protecting and improving environmental quality (Robertson and Swinton, 2005). The need to answer this question is particularly acute in the midwestern United States, one of the largest regions of intensive, rain-fed agriculture in the world. Crop production in this region currently relies heavily on synthetic N fertilizer and herbicides to manage soil fertility and weeds (National Agricultural Statistics Service, 2003, 2007a). Concomitantly, N and herbicides emitted from midwestern cropland are detected regularly in ground and surface waters, and are viewed by many analysts as important environmental contaminants that require improved management approaches (Goolsby et al., 1999; Dinnes et al., 2002; Gilliom et al., 2006). The midwestern United States has also been a major recipient of agricultural subsidy payments from the federal government (Environmental Working Group, 2007), and there are persistent questions concerning farm economic viability if these subsidies were removed due to global trade agreements or changes in domestic farm policy.

The *Alternative Agriculture* report of the National Research Council (1989) focused public and scientific attention on alternative farming systems that, in comparison with conventional systems, rely more on intensive management of ecological relationships than on purchased fertilizers and pesticides to maintain productivity and profitability. The report noted that alternative systems that use diverse sequences of crops, mixed crop–livestock production, and integrated pest management strategies may reduce "adverse environmental and health effects without decreasing–and in some cases increasing–per acre crop yields and the productivity of livestock management systems."

Both LEI and organic farming systems are alternatives to conventional agriculture that rely heavily on ecological processes for soil fertility and pest management. Managers of both LEI and organic systems seek to reduce costs, maintain or increase yields, and improve profitability through an iterative process of adaptive management whereby soil, crop, and pest conditions are monitored and analyzed, and farming practices are adjusted to maximize the beneficial impacts of ecological interactions (Vereijken, 1992; Shea et al., 1998; Deming et al., 2007). The LEI systems differ from organic systems in that they may include some use of synthetic fertilizers and pesticides and generally operate without price premiums for crop and livestock products.

Crop N demands in LEI systems can be met with N released from decomposing legume residues and manure supplemented

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Abbreviations: LEI, low-external-input.

with synthetic fertilizer (Fox and Piekielek, 1988; Morris et al., 1993; Magdoff et al., 1997). Weeds may be controlled in LEI systems by combining cultivation with low levels of herbicides within diverse crop sequences that challenge weeds with a broad range of stress and mortality factors (Buhler et al., 1992; Mulder and Doll, 1993; Liebman and Staver, 2001). These and certain other LEI approaches for managing soil fertility and weeds offer substantial opportunities for reducing pollution by agrichemicals and improving water quality (Dinnes et al., 2002; Gilliom et al., 2006).

To date, evidence for the ability of farming systems to produce high yields and sufficient income with reduced levels of agrichemical inputs has been inconsistent. Whereas some comparative systems experiments have shown that fertilizer and pesticide use can be reduced substantially without compromising yields and profits (Vereijken, 1986; Jordan and Hutcheon, 1995; Wijnands, 1997; Gallandt et al., 1998; Porter et al., 2003), others have shown that LEI systems fall below the yield and profit levels achieved in conventional systems (Klonsky and Livingston, 1994; Munn et al., 1998; VanGessel et al., 2004). These divergent results emphasize the need to better understand the performance characteristics of contrasting cropping systems. Consequently, we conducted a multiyear, 9-ha field experiment to test the hypothesis that LEI systems can provide yields and net returns that match or exceed those obtained from conventional systems. Because weeds pose a recurrent and nearly ubiquitous challenge to LEI systems, we also tested the hypothesis that LEI systems can suppress weeds as effectively as conventional systems.

MATERIALS AND METHODS

Experimental Site, Rotation Systems, and Crop Management

The experiment was conducted at the Iowa State University Marsden Farm, in Boone County, Iowa (42°01' N; 93°47' W; 333 m above sea level). Soils at the site are Clarion loam (fine-loamy, mixed, superactive, mesic, Typic Hapludolls), Nicollet loam (fine-loamy, mixed, superactive, mesic, Aquic Hapludolls), and Webster silty clay loam (fine-loamy, mixed, superactive, mesic, Typic Endoaquolls). Soil samples taken to a depth of 20 cm on 8 Nov. 2002 indicated a mean buffer pH of 6.8, a mean organic matter concentration (via combustion analysis) of 51 g kg^{-1}, a mean P concentration (via the Bray-1 procedure) of 31 mg kg^{-1}, and a mean K concentration (via ammonium acetate extraction) of 167 mg kg^{-1}.

Before the initiation of the experiment, the site had been managed for at least 20 yr with a corn–soybean rotation receiving conventional fertilizer and herbicide inputs. The entire site was planted with oat in 2001 and the cropping systems experiment was established in 2002. The experiment was arranged as a randomized complete block design with each crop phase of each rotation system present every year in four replicate blocks. Plot size was 18 by 85 m. Weather data were collected about 1 km from the study site.

Three crop rotations suitable for the midwestern United States were included in the study. The 2-yr (corn/soybean) rotation is typical of cash grain farming systems in the region and was managed with conventional fertilizer and herbicide inputs. The 3-yr (corn/soybean/small grain + red clover green manure) and 4-yr (corn/soybean/small grain + alfalfa/alfalfa hay) rotations are representative of diversified farming systems in the region, which often include swine (*Sus scrofa*) or cattle (*Bos taurus*). Compared to the 2-yr rotation, the 3- and 4-yr rotations received lower synthetic N fertilizer and herbicide inputs. Spring triticale (× *Triticosecale* Wittmack) was used as the small grain in 2003–2005, and oat (*Avena sativa* L.) was used in 2006.

Crop identities, planting and harvest dates, seeding rates, and row spacings are shown in Table 1. A nongenetically engineered soybean variety was used in all systems in 2003 to 2005. In 2006, a glyphosate-tolerant soybean variety was used in the 2-yr system, whereas a nongenetically engineered variety was used in the 3- and 4-yr systems. Red clover and alfalfa were planted with triticale or oat. First-year alfalfa was not harvested in 2003, but was harvested once in 2004 to 2006. Established second-year alfalfa was harvested three times in 2003, and four times in 2004 to 2006. Red clover was used solely as a green manure and was not harvested for forage in any year. Soybean, red clover, and alfalfa seeds were treated with appropriate *Rhizobium* and *Bradyrhizobium* inoculants before planting. Triticale and oat straw was baled and removed after grain harvest.

Synthetic fertilizers were applied in the 2-yr rotation at conventional rates based on soil tests, whereas composted cattle manure and reduced rates of synthetic fertilizers were applied in the 3- and 4-yr rotations (Table 2). Composted manure was applied in October of each year at a rate of 15.7 Mg ha^{-1} (fresh weight basis) to plots of red clover in the 3-yr rotation and to plots of established alfalfa in the 4-yr rotation. This corresponded to a mean dry matter application rate of 10.2 Mg ha^{-1}. Calculated application rates of total N, P, and K in composted manure, reflecting analyses conducted by the Iowa State University Soil and Plant Analysis Laboratory, are shown in Table 2. Based on soil test results, lime was applied on 12 Mar. 2004, and a mixture of monoammonium phosphate and muriate of potash was applied on 27 Oct. 2005 (Table 2). The late spring nitrate test (Blackmer et al., 1997) was used for corn in all rotation systems to determine rates for post-emergence side-dress N applications (Table 2).

Weed management in the 2-yr rotation was based largely on herbicides applied at conventional rates (Table 3). In the 3- and 4-yr systems, herbicides were applied in 38-cm-wide bands in corn and soybean, greater reliance was placed on cultivation, and no herbicides were applied in small grain and forage legume crops (Table 3). Choices of post-emergence herbicides used in each of the systems were made based on the identities, densities, and sizes of weed species observed in the plots. Stubble of small grain crops in the 3- and 4-yr systems was mowed to suppress weeds 19 to 28 d after grain harvest.

Tillage regimes differed among rotation systems. In the 2-yr system, a combination of fall chisel plowing and spring field cultivation was used between corn harvest and soybean planting, and spring field cultivation was used between soybean harvest and corn planting. In the 3-yr system, a combination of fall chisel plowing and spring field cultivation was used between corn harvest and soybean planting; zero tillage or spring disking was used between soybean harvest and small grain and red clover planting; and fall moldboard plowing, followed by spring

Table 1. Crop identities, planting and harvest dates, seeding rates, and row spacings used in 2003 to 2006.

Year	Crop	Rotation system	Hybrid or cultivar	Planting date	Harvest date(s)	Seed density	Seed mass	Interrow spacing
						seeds ha^{-1}	kg ha^{-1}	cm
2003	corn	all	Golden Harvest 8562	23 Apr.	2 Oct.	79,040	–	76
2004	corn	all	Golden Harvest 8562	23 Apr.	15 Oct.	79,040	–	76
2005	corn	all	Agrigold 6395	27 Apr.	22 Sept.	79,530	–	76
2006	corn	all	Agrigold 6395	24 Apr.	2 Oct.	79,530	–	76
2003	soybean	all	Asgrow 2869	29 May	7 Oct.	387,340	–	76
2004	soybean	all	Asgrow 2869	29 May	6 Oct.	387,340	–	76
2005	soybean	all	Asgrow 2869	10 May	4 Oct.	387,340	–	76
2006	soybean	2-yr	Kruger 287RR	17 May	9 Oct.	408,850	–	76
2006	soybean	3-yr and 4-yr	Kruger 2918	17 May	9 Oct.	408,850	–	76
2003	triticale	3-yr and 4-yr	Trical 37812	26 Mar.	23 July	–	110	20
2004	triticale	3-yr and 4-yr	Trical 37812	5, 6 Apr.	23 July	–	122	20
2005	triticale	3-yr and 4-yr	Trical 37812	29 Mar.	14 July	–	122	20
2006	oat	3-yr and 4-yr	IN09201	6, 10 Apr.	18 July	–	56	20
2003	red clover	3-yr	Cherokee	26 Mar.	–	–	13	20
2004	red clover	3-yr	Cherokee	5, 6 Apr.	–	–	13	20
2005	red clover	3-yr	Cherokee	29 Mar.	–	–	13	broadcast
2006	red clover	3-yr	Cherokee	6, 10 Apr.	–	–	13	20
2002	alfalfa	4-yr	Dekalb 3720	20 Aug.	2003: 13 June, 11 July, 19 Aug.	–	19	20
2003	alfalfa	4-yr	Dekalb 3720	26 Mar.	2004: 1 June, 30 June, 11 Aug., 13 Sept.	–	17	20
2004	alfalfa	4-yr	Dekalb 3720	5, 6 Apr.	2004: 13 Sept.; 2005: 1 June, 1 July, 8 Aug., 14 Sept.	–	17	20
2005	alfalfa	4-yr	Farm Science Genetics 300LH	29 Mar.	2005: 14 Sept.; 2006: 26 May, 26 June, 31 July, 25 Sept.	–	17	broadcast
2006	alfalfa	4-yr	Farm Science Genetics 400LH	6, 10 Apr.	2006: 1 Sept.	–	17	20

Table 2. Synthetic and organic soil fertility amendments for crops grown in contrasting rotation systems in 2003 to 2006.

Rotation	Crop	2003	2004	2005	2006
2-yr	corn	112 kg N ha^{-1} as urea, at planting; 39 kg N ha^{-1} as urea, side-dressed	112 kg N ha^{-1} as urea, at planting	112 kg N ha^{-1} as urea, at planting	18 kg N + 20 kg P + 112 kg K ha^{-1} as MAP† and KCl, before planting; 112 kg N ha^{-1} as urea, at planting; 28 kg N ha^{-1} as UAN‡, side-dressed
2-yr	soybean	none	none	none	18 kg N + 20 kg P + 112 kg K ha^{-1} as MAP and KCl, before planting
3-yr	corn	114 kg N + 43 kg P + 141 kg K ha^{-1} as composted manure, before planting; 56 kg N ha^{-1} as urea, at planting; 39 kg N ha^{-1} as urea, side-dressed	58 kg N + 38 kg P + 117 kg K ha^{-1} as composted manure, before planting; 34 kg N ha^{-1} as urea, at planting; 73 kg N ha^{-1} as UAN, side-dressed	205 kg N + 84 kg P + 222 kg K ha^{-1} as composted manure, before planting	18 kg N + 20 kg P + 112 kg K ha^{-1} as MAP and KCl, before planting; 148 kg N + 68 kg P + 160 kg K ha^{-1} as composted manure, before planting
3-yr	soybean	none	none	none	18 kg N + 20 kg P + 112 kg K ha^{-1} as MAP and KCl, before planting
3-yr	triticale/clover or oat/clover	28 kg N ha^{-1} as urea, at planting	28 kg N ha^{-1} as urea, at planting	28 kg N ha^{-1} as urea, at planting	18 kg N + 20 kg P + 112 kg K ha^{-1} as MAP and KCl, before planting
4-yr	corn	114 kg N + 43 kg P + 141 kg K ha^{-1} as composted manure, before planting; 56 kg N ha^{-1} as urea, at planting	58 Kg N + 38 kg P + 117 kg K ha^{-1} as composted manure, before planting; 34 kg N ha^{-1} as urea, at planting; 36 kg N ha^{-1} as UAN, side-dressed	205 kg N + 84 kg P + 222 kg K ha^{-1} as composted manure, before planting	18 kg N + 20 kg P + 112 kg K ha^{-1} as MAP and KCl, before planting; 148 kg N + 68 kg P + 160 kg K ha^{-1} as composted manure, before planting
4-yr	soybean	none	none	none	18 kg N + 20 kg P + 112 kg K ha^{-1} as MAP and KCl, before planting
4-yr	triticale/alfalfa or oat/alfalfa	28 kg N ha^{-1} as urea, at planting	28 kg N ha^{-1} as urea, at planting	28 kg N ha^{-1} as urea, at planting	18 kg N + 20 kg P + 112 kg K ha^{-1} as MAP and KCl, before planting
4-yr	alfalfa	none	none	none	18 kg N + 20 kg P + 112 kg K ha^{-1} as MAP and KCl

† MAP: monoammonium phosphate.

‡ UAN: urea ammonium nitrate.

Table 3. Mechanical and chemical weed management practices for crops grown in contrasting rotation systems in 2003 to 2006. Dosages of herbicide active ingredients (kg ha^{-1}) are shown in parentheses.

Rotation	Crop	2003	2004	2005	2006
2-yr	corn	rotary hoeing (1×); PPI†, broadcast: S-metolachlor‡ (1.60), isoxaflutole§ (0.105); POST¶, broadcast: nicosulfuron# (0.026), rimsulfuron†† (0.013), mesotrione‡‡ (0.070)	PRE‡‡‡, broadcast: S-metolachlor (1.60), isoxaflutole (0.105)	PRE, broadcast: S-metolachlor (1.97), isoxaflutole (0.070); POST, broadcast: nicosulfuron (0.026), rimsulfuron (0.013)	PRE, broadcast: S-metolachlor (1.14), isoxaflutole (0.088)
2-yr	soybean	PPI, broadcast: S-metolachlor (1.60); POST, broadcast: bentazon§§ (1.12), flumiclorac pentyl ester¶¶ (0.060), clethodim## (0.180)	PRE, broadcast: S-metolachlor (1.60); POST, broadcast: bentazon (1.12), clethodim (0.105)	PRE, broadcast: S-metolachlor (1.81); POST, broadcast: flumiclorac pentyl ester (0.034)	POST, broadcast: glyphosate as isopropylamine salt§§§ (2.25)
3-yr	corn	rotary hoeing (1×); interrow cultivation (2×); POST, banded†††: nicosulfuron (0.013), rimsulfuron (0.007), mesotrione (0.035)	rotary hoeing (1×); interrow cultivation (1×); POST, banded: nicosulfuron (0.013), rimsulfuron (0.007), mesotrione (0.047)	rotary hoeing (1×); interrow cultivation (2×); POST, banded: nicosulfuron (0.013), rimsulfuron (0.007), mesotrione (0.047)	rotary hoeing (1×); interrow cultivation (2×); POST, banded: nicosulfuron (0.013), rimsulfuron (0.007), mesotrione (0.053)
3-yr	soybean	rotary hoeing (1×); interrow cultivation (1×); PPI, broadcast: S-metolachlor (1.60); POST, banded: flumiclorac pentyl ester (0.030)	rotary hoeing (1×); interrow cultivation (2×); PRE, broadcast: S-metolachlor (1.60); POST, banded: bentazon (0.56)	rotary hoeing (1×); interrow cultivation (1×); PRE, broadcast: S-metolachlor (1.81); POST, banded: flumiclorac pentyl ester (0.017)	rotary hoeing (1×); interrow cultivation (1×); POST, banded: flumiclorac pentyl ester (0.015), clethodim (0.051), lactofen (0.053)
3-yr	triticale/clover or oat/clover	stubble mowing (1×)	stubble mowing (1×)	stubble mowing (1×)	stubble mowing (1×)
4-yr	corn	rotary hoeing (1×); interrow cultivation (2×); POST, banded: nicosulfuron (0.013), rimsulfuron (0.007), mesotrione (0.035)	rotary hoeing (1×); interrow cultivation (1×); POST, banded: nicosulfuron (0.013), rimsulfuron (0.007), mesotrione (0.047)	rotary hoeing (1×); interrow cultivation (2×); POST, banded: nicosulfuron (0.013), rimsulfuron (0.007), mesotrione (0.047)	rotary hoeing (1×); interrow cultivation (2×); POST, banded: nicosulfuron (0.013), rimsulfuron (0.007), mesotrione (0.053)
4-yr	soybean	rotary hoeing (1×); interrow cultivation (1×); PPI, broadcast: S-metolachlor (1.60); POST, banded: flumiclorac pentyl ester (0.030)	rotary hoeing (1×), interrow cultivation (2×); PRE, broadcast: S-metolachlor (1.60); POST, banded: bentazon (0.56)	rotary hoeing (1×), interrow cultivation (1×); PRE, broadcast: S-metolachlor (1.81); POST, banded: flumiclorac pentyl ester (0.017)	rotary hoeing (1×); interrow cultivation (1×); POST, banded: flumiclorac pentyl ester (0.015), clethodim (0.051), lactofen (0.053)
4-yr	triticale/alfalfa or oat/alfalfa	stubble mowing (1×)	stubble mowing (1×), hay removal (1×)	stubble mowing (1×), hay removal (1×)	stubble mowing (1×), hay removal (1×)
4-yr	alfalfa	hay removal (3×)	hay removal (4×)	hay removal (4×)	hay removal (4×)

† PPI: pre-plant incorporation.

‡ S-metolachlor: acetamide, 2-chloro-*N*-(2-ethyl-6-methylphenyl)-N-(2-methoxy-1-methylethyl)-,(S).

§ Isoxaflutole: 5-cyclopropyl-4-(2-methylsulfonyl-4-trifluoromethylbenzoyl) isoxazole.

¶ POST: post-emergence application.

Nicosulfuron: 2-((4,6-dimethoxypyrimidin-2-yl)aminocarbonyl) aminosulfonyl-N,N-dimethyl-3-pyridinecarboxamide.

†† Rimsulfuron: N((4,6- dimethoxypyrimidin-2-yl)amino]carbonyl)-3-(ethylsulfonyl)-2-pyridine sulfonamide.

‡‡ Mesotrione: (2-(4-methylsulfonyl)-2-nitrobenzoyl)-1,3-cyclohexanedione.

§§ Bentazon: 3-(1-methylethyl)-1H-2,1,3-benzothiadiazin-4(3H)-one 2,2-dioxide.

¶¶ Flumiclorac pentyl ester: (pentyl(2-chloro-4-fluoro-5-(1,3,4,5,6,7-hexahydro-1,3-dioxo2H-isoindol-2-yl)phenoxy)acetate.

Clethodim: (E)-2-(1-(((3-chloro-2-propenyl)oxy)imino)propyl)-5-(2-(ethylthio)propyl)-3-hydroxy-2-2cyclohenen-1-one.

††† Dosages for band applications have been adjusted for the 50% reduction in land area covered.

‡‡‡ PRE: pre-emergence application.

§§§ Glyphosate: N-(phosphonomethyl) glycine in the form of its isopropylamine salt.

disking and field cultivation were used to incorporate clover sod and prepare a seedbed for corn. Tillage practices in the 4-yr system were the same as in the 3-yr system, except for a longer period without soil disturbance, from small grain and alfalfa establishment until alfalfa sod was moldboard plowed in the fall.

In establishing the experiment during 2001 to 2002, cropping patterns similar to those described above were used, with several exceptions. Alfalfa preceding the 2003 corn crop in the 4-yr rotation was established with oat on 27 Mar. 2002, harvested twice (18 June and 19 Aug. 2002), and then moldboard plowed on 12 Nov. 2002. Consequently, the 2003 corn crop followed an alfalfa stand that was a year younger than the alfalfa stands preceding the 2004 to 2006 corn crops. Additionally, winter triticale, rather than spring triticale or oat, was planted in the 3- and 4-yr rotations on 25 Sept. 2001. Red clover and alfalfa were frost seeded into triticale on 28 Feb. 2002, but established poorly. Subsequently, hairy vetch (*Vicia villosa* Roth) was drilled into triticale stubble in the 3-yr rotation on 26 June 2002 and moldboard plowed on 12 Nov. 2002. Alfalfa was drilled into triticale stubble in the 4-yr rotation on 20 Aug. 2002 and allowed to grow the following year as a hay crop.

Crop Sampling and Data Analysis

Yields of corn and soybean were determined from the central 12 rows (775 m^2) of each plot using a combine and a weigh wagon.

Triticale and oat grain yields were determined in the same way from entire plots (1550 m^2). Yields of triticale and oat straw and alfalfa hay were determined by weighing bales harvested from entire plots. After determining crop moisture concentrations, yields were adjusted to moisture levels of 155 g kg^{-1} for corn, 130 g kg^{-1} for soybean, 135 g kg^{-1} for triticale grain, 140 g kg^{-1} for oat grain, 110 g kg^{-1} for straw, and 150 g kg^{-1} for alfalfa hay. Because initial analyses indicated significant year by treatment interactions, crop yields were analyzed separately by year with analysis of variance models that included rotation system as a fixed factor and block as a random factor. Two orthogonal contrasts were used for analyses of crop yield data: (i) the 2-yr rotation vs. the average of the 3- and 4-yr rotations and (ii) the 3-yr vs. the 4-yr rotation.

Weed Manipulations, Sampling, and Data Analysis

Weed responses to the three rotation systems were studied in two ways. The first approach ("pulse-chase") involved adding a pulse of velvetleaf and giant foxtail seeds to subplot areas of each rotation system × crop phase main plot and measuring subsequent changes in seed density in soil. Both velvetleaf and giant foxtail are commonly encountered in midwestern U.S. crop fields (Bridges and Bauman, 1992). The second approach ("ambient weeds") involved measuring the biomass of weed species whose densities were not experimentally augmented, but which were affected by the chemical, mechanical, and cultural control practices associated with each rotation system.

To determine background population densities of velvetleaf and giant foxtail seeds, 40 19-mm-diam. soil cores were extracted to a depth of 20 cm in 7 by 7 m subplot areas of each main plot between 22 Oct. and 1 Nov. 2002. The cores were then washed in an elutriator to separate weed seeds from soil (Wiles et al., 1996), and viable velvetleaf and giant foxtail seeds were enumerated using direct germination and tetrazolium tests. The resulting data indicated background densities of viable velvetleaf and giant foxtail seeds to be low (velvetleaf: 4 ± 2 seeds m^{-2}; giant foxtail: 21 ± 7 seeds m^{-2}; mean ± SE). Locally harvested velvetleaf and giant foxtail seeds were then added at rates of 470 and 1876 viable seeds m^{-2}, respectively, to the surface of each subplot during 4 to 7 Nov. 2002. Velvetleaf and giant foxtail seed densities were determined again on 10 to 11 Apr. 2006 by collecting 40 32-mm-diam. soil cores to a depth of 20 cm in each subplot, washing them in an elutriator, and then measuring viable seed densities through direct germination and tetrazolium testing.

Repeated measures analysis of variance was used to test for differences among rotation systems in velvetleaf and giant foxtail seed densities between November 2002 and April 2006. Rotation system was used as a fixed factor and block as a random factor. Starting densities of viable seeds in each pulse-chase subplot were set at background densities plus pulse densities. Because the primary focus of the analyses was on differences among rotation systems, repeated measures ANOVAs were conducted using per-block means for each rotation, calculated by averaging seed densities over all crop phases in a rotation for each of the four replicate blocks.

Ambient weed biomass was determined in corn plots by clipping, drying, and weighing shoot material collected from eight 3.05 by 0.76-m sampling areas in each plot on 25 Sept. 2003, 5 Oct. 2004, 21 Sept. 2005, and 26 Sept. 2006. Sampling areas were not within the pulse-chase subplots. Weed biomass in soybean plots was determined in the same manner on 6 Oct. 2003, 5 Oct. 2004, 21 Sept. 2005, and 26 Sept. 2006. Weed biomass in small grain stubble with red clover and alfalfa, and second year alfalfa was determined by clipping, drying, and weighing shoot material collected in eight 0.25-m^2 quadrats in each plot on 9 Oct. 2003, 8 Oct. 2004, 29 Sept. 2005, and 28 Sept. 2006. Weed biomass data were analyzed separately by year with ANOVA models that included rotation system as a fixed factor and block as a random factor. The same two orthogonal contrasts used for analyses of crop yields were used to test for differences in weed biomass within the same crop among rotation systems, and among rotation systems averaged over crop phases.

Economic Analyses

Economic performance of the different crops and rotation systems was assessed using (i) data from the experimental plots concerning machinery operations, inputs, and yields; (ii) costs of seeds, fertilizers, and herbicides at local agricultural dealers; (iii) agricultural engineering and farm business management data bases (Hanna, 2001; Edwards, 2005a; Duffy and Smith, 2006 and previous years); and (iv) central Iowa, state, and national-level market prices and subsidies for crops (Edwards 2005b; National Agricultural Statistics Service, 2006). Manure was assumed to be free (i.e., generated by on-farm livestock), but labor and machinery costs were assigned to spreading it. All crop expenses and incomes were accounted for in the year the crop was produced. Consequently, seed costs for alfalfa and income from hay produced during the alfalfa seeding year were assigned to the small grain phase of the 4-yr system. Yearly costs and returns to land and management were calculated for the different crops and rotation systems in 2003–2006, and economic analyses were conducted using averages of these values.

RESULTS

Weather Conditions

Temperature conditions during 2003 to 2006 did not deviate greatly from long-term averages, with the exception of June, July, and August 2004, which were cooler than usual (Table 4). Variation in precipitation during the 2003 to 2006 growing seasons was more marked. July 2003, May 2004, and August and September 2005 and 2006 were exceptionally wet, whereas August 2003, July and September 2004, and May and June 2006 were abnormally dry (Table 4). Several plots were flooded for up to 3 or 4 d in spring 2004, but in general, crop growth conditions during the period of the experiment were good to excellent.

Synthetic N fertilizer and herbicide use

Use of the late spring soil nitrate test to guide post-emergence N fertilizer rates for corn (Blackmer et al., 1997) led to variation among years and cropping systems in synthetic N use (Table 2). This variation reflected differences in weather conditions, quantities and qualities of previous crop residues, and manure amendments. Synthetic N inputs for corn were, however, consistently higher in the 2-yr system than in the 3- and 4-yr systems (Table 2). Across years, the mean synthetic N use for corn was 133 kg N ha^{-1} yr^{-1} in the 2-yr system, 55 kg N ha^{-1} yr^{-1} in the 3-yr system, and 36 kg N ha^{-1} yr^{-1} in the 4-yr system (Table 2). Total synthetic N use in the three rotation systems followed a pattern similar to that for corn. Averaged across 2003–2006 and the different phases of each rotation system, mean synthetic N use was 59% lower in the 3-yr system (28 kg ha^{-1} yr^{-1}) and 74% lower in the 4-yr system (18 kg ha^{-1} yr^{-1}) than in the 2-yr system (69 kg N ha^{-1} yr^{-1}) (Fig. 1A).

Table 4. Mean monthly air temperature and total monthly precipitation during the 2003 to 2006 growing seasons, and long-term temperature and precipitation averages (1951–2006), at the experiment site.

Month	Temperature					Precipitation				
	2003	2004	2005	2006	Long-term avg.	2003	2004	2005	2006	Long-term avg.
	°C					mm				
April	10	11	12	12	10	112	61	84	109	88
May	14	16	14	16	16	102	208	111	55	113
June	20	19	22	22	21	150	91	124	21	125
July	22	21	23	24	23	168	50	104	141	102
August	23	19	22	22	22	25	132	172	156	105
September	16	19	20	16	18	100	34	111	191	88
October	12	11	11	9	11	24	45	9	64	59
November	2	4	3	4	3	109	76	33	40	43

Herbicide use was consistently lower for corn and soybean in the 3- and 4-yr systems than in the 2-yr system, due to the use of banded post-emergence materials rather than broadcast applications of pre- and post-emergence materials (Table 3). Averaged across 2003–2006, mean herbicide use in corn was 1.700 kg a.i. ha^{-1} yr^{-1} in the 2-yr system, but only 0.066 kg a.i. ha^{-1} yr^{-1} in the 3- and 4-yr systems. For soybean, mean herbicide use across years was 2.470 kg a.i. ha^{-1} yr^{-1} in the 2-yr system as compared with 1.434 kg a.i. ha^{-1} yr^{-1} in the 3- and 4-yr systems. A sharp drop in herbicide use occurred in the LEI systems in 2006, when post-emergence materials became the only herbicides applied in soybean (Table 3). Averaged across years and the different phases of each rotation system, mean herbicide inputs were 76% lower in the 3-yr system (0.500 kg a.i. ha^{-1} yr^{-1}) and 82% lower in the 4-yr system (0.375 kg a.i. ha^{-1} yr^{-1}) than in the 2-yr system (2.085 kg a.i. ha^{-1} yr^{-1}) (Fig. 1B).

Crop Yields

Corn and soybean yields in the LEI 3- and 4-yr systems matched (2003 and 2004) or exceeded (2005 and 2006) levels obtained from the conventionally managed 2-yr system (Table 5). To provide a context for these productivity data, we note that corn and soybean yields in all of the experimental systems were similar to or greater than mean yields of commercial farms in Boone County in all 4 yr of the experiment (Table 5).

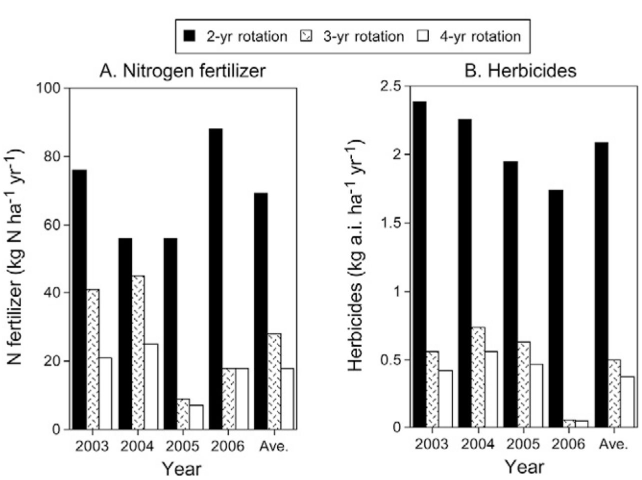

Fig. 1. (A) Synthetic N fertilizer and (B) herbicide active ingredients used in each rotation system, by year. The values shown represent the sums of the mass of materials applied per unit area in each of phase of each rotation system, divided by the length, in years, of the rotation.

Small grain yields did not differ between the 3-yr and 4-yr systems (Table 5), but were markedly lower in 2004 than in other years, due to higher disease incidence and severity (data not shown). Mean county commercial yields for triticale were not available, but yield of oat in both the 3- and 4-yr systems exceeded mean oat yield for Boone County in 2006 (Table 5).

Alfalfa hay yields in the 4-yr system (Table 5) rose steadily between 2003 and 2006, perhaps reflecting a negative effect of the short establishment period during 2002 for the 2003 hay crop (Table 1), and a beneficial effect of composted manure and synthetic P and K fertilizers preceding the 2006 hay crop (Table 2). Second-year alfalfa hay yields in experiment plots were similar to or greater than mean yields of established alfalfa on commercial farms in Boone County in 2003 to 2006 (Table 5).

Weed Seed Density and Biomass

Giant foxtail seed population density in the surface 20 cm of soil in subplot areas with experimentally supplemented seed banks declined significantly between fall 2002 and spring 2006 in all of the rotation systems (Fig. 2A). The decline was greatest in the 2-yr system, least in the 3-yr system, and intermediate in the 4-yr system (Fig. 2A). Velvetleaf seed population density in subplots with supplemented seed banks declined significantly in the 2-

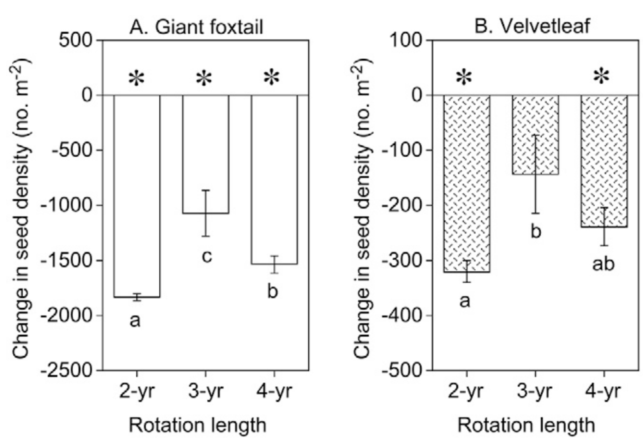

Fig. 2. Change in viable seed densities of (A) giant foxtail and (B) velvetleaf between November 2002 and April 2006 in each rotation system, in the top 20 cm of soil. Means and their standard errors are shown. Negative values indicate a decline in mean seed densities over time. Asterisks indicate a significant difference (*P* < 0.05, two-tailed test) between the value shown and 0. Within a species, values represented by columns not underwritten with the same lowercase letter are significantly different (*P* < 0.05).

Table 5. Yields of corn, soybean, triticale and oat grain, and alfalfa hay from experimental plots and from commercial farms in Boone County, Iowa, 2003 to 2006.

Crop	Year	Rotation system 2-yr	3-yr	4-yr	SE	Boone Co. mean yield†	Contrasts 2-yr vs. (3-yr + 4-yr)/2	3-yr vs. 4-yr
		Mg ha^{-1}					*P*	
Corn	2003	12.01	11.77	11.51	0.31	10.69	0.3010	0.5115
Corn	2004	12.84	12.87	13.24	0.51	12.05	0.7352	0.6210
Corn	2005	12.45	14.28	14.14	0.37	12.07	0.0085	0.7988
Corn	2006	12.75	13.01	13.39	0.11	10.83	0.0156	0.0533
Soybean	2003	2.98	2.88	2.94	0.13	2.34	0.6665	0.7348
Soybean	2004	3.63	4.03	3.98	0.14	3.49	0.0674	0.7988
Soybean	2005	3.98	4.29	4.31	0.09	3.78	0.0277	0.8526
Soybean	2006	2.96	3.36	3.33	0.07	3.36	0.0049	0.8032
Triticale‡	2003	–	5.15	4.99	0.05	na	–	0.0997
Triticale‡	2004	–	2.56	2.56	0.08	na	–	0.9900
Triticale‡	2005	–	4.09	4.41	0.17	na	–	0.2736
Oat‡	2006	–	4.78	4.75	0.14	3.45	–	0.8803
Alfalfa§	2003	–	–	8.53	0.11	8.31	–	–
Alfalfa§	2004	–	–	8.94	0.69	9.00	–	–
Alfalfa§	2005	–	–	10.03	0.36	8.58	–	–
Alfalfa§	2006	–	–	11.02	0.52	7.03	–	–

† Data from National Agricultural Statistics Service (2007b).

‡ Mean yield of harvested triticale and oat straw in the 3- and 4-yr rotations was 0.90 Mg ha^{-1} in 2003, 1.64 Mg ha^{-1} in 2004, 2.61 Mg ha^{-1} in 2005, and 2.13 Mg ha^{-1} in 2006.

§ Total alfalfa hay yield for second-year stands. Mean first-year yield was 0 Mg ha^{-1} in 2003, 1.12 Mg ha^{-1} in 2004, 0.94 Mg ha^{-1} in 2005, and 2.58 Mg ha^{-1} in 2006.

Table 6. Weed biomass in different crops and rotations in 2003 to 2006.

Crop(s)	Year	Rotation 2-yr†	3-yr†	4-yr†	SE‡	Contrasts 2-yr vs. (3-yr + 4-yr)/2	3-yr vs. 4-yr
		g m^{-2}				*P*	
Corn	2003	0.1 (0.10)	1.6 (0.67)	0.1 (0.09)	(0.23)	0.3736	0.1280
Corn	2004	0.1 (0.10)	0.2 (0.14)	0.0 (0.03)	(0.10)	0.9192	0.4435
Corn	2005	0.1 (0.05)	0.1 (0.05)	0.1 (0.12)	(0.04)	0.4720	0.2418
Corn	2006	0.1 (0.11)	0.0 (0.04)	0.0 (0.02)	(0.05)	0.2819	0.7574
Soybean	2003	0.0 (0.04)	2.1 (0.77)	4.2 (1.04)	(0.36)	0.0940	0.6175
Soybean	2004	0.6 (0.38)	1.2 (0.44)	0.4 (0.24)	(0.36)	0.9337	0.7070
Soybean	2005	0.3 (0.24)	0.1 (0.08)	0.0 (0.00)	(0.09)	0.1359	0.5952
Soybean	2006	0.0 (0.00)	0.0 (0.00)	0.8 (0.37)	(0.19)	0.4657	0.2261
Triticale	2003	–	15.1 (2.59)	32.0 (3.35)	(0.49)	–	0.3578
Triticale	2004	–	1.7 (0.53)	0.3 (0.21)	(0.42)	–	0.6227
Triticale	2005	–	13.1 (2.44)	0.5 (0.38)	(0.26)	–	0.0118
Oat	2006	–	4.4 (1.69)	1.7 (0.90)	(0.17)	–	0.0453
Alfalfa	2003	–	–	3.2 (0.99)	(0.58)	–	–
Alfalfa	2004	–	–	0.3 (0.23)	(0.15)	–	–
Alfalfa	2005	–	–	0.0 (0.01)	(0.01)	–	–
Alfalfa	2006	–	–	0.7 (0.51)	(0.13)	–	–
Rotation ave.	2003	0.1 (0.07)	6.2 (1.34)	9.9 (1.36)	(0.14)	0.0003	0.9221
Rotation ave.	2004	0.4 (0.24)	1.3 (0.37)	0.2 (0.18)	(0.21)	0.8952	0.5405
Rotation ave.	2005	0.2 (0.14)	4.4 (0.85)	0.2 (0.13)	(0.06)	0.0040	0.0002
Rotation ave.	2006	0.6 (0.05)	1.5 (0.58)	0.8 (0.45)	(0.05)	0.0002	0.0939

† Means of untransformed and $\log_e(x + 1)$ transformed data. The latter are in parentheses.

‡ Standard errors of $\log_e(x + 1)$ transformed data.

and 4-yr systems, but remained unchanged in the 3-yr system (Fig. 2B). Reductions in velvetleaf seed density did not differ between the 2- and 4-yr systems (Fig. 2B).

Common waterhemp (*Amaranthus rudis* Sauer) and woolly cupgrass [*Eriochloa villosa* (Thunb.) Kunth.] were the dominant species contributing to weed biomass production in plot areas used for ambient weed measurements (data not shown). Ambient weed biomass in corn and soybean did not differ among management systems and was low (<4.2 g m^{-2}) in all years (Table 6). Weed biomass in small grain stubble and intercropped legumes did not differ between the 3- and 4-yr systems in 2003 and 2004, but was greater in the 3-yr system in 2005 and 2006 (Table 6). Weed biomass in established alfalfa was extremely low in all years and similar to levels measured in corn and soybean (Table 6).

Economic Performance Characteristics

Averaged over the period 2003 to 2006, gross revenue was greatest in the 2-yr system, least in the 3-yr system, and intermediate in the 4-yr system (Table 7). Differences in gross revenue among the systems did not reflect differences in revenues from corn and soybean, since revenues for those crops were higher in the LEI systems than the conventional system (Table 7), due to higher average yields (Table 5). Rather, lower overall gross revenue from the LEI systems reflected low revenue from triticale and oat. Gross revenue from established alfalfa was intermediate between revenue from corn and soybean (Table 7).

Total production costs, excluding labor, were lowest for the 4-yr system, highest for the 2-yr system, and intermediate for the 3-yr system (Table 7). Cost savings for the LEI systems relative to the conventional system were most marked for herbicides and synthetic N fertilizer (data not shown). In contrast, labor requirements and associated labor costs were highest in the 4-yr system, least in the 2-yr system, and intermediate in the 3-yr system (Table 7). In particular, corn in the LEI systems had higher labor requirements than corn in the conventional system, due to added work for spreading composted manure, plowing legume sod, and cultivations. Alfalfa hay production in the 4-yr system also had a large labor requirement relative to corn and soybean production in the conventional 2-yr system.

Despite lower gross revenue and higher labor requirements, returns to land and management without subsidies were 7.1% higher for the LEI 4-yr system than for the conventional 2-yr system, due to the large reduction in overall production costs (Table 7). Returns to land and management without subsidies were, however, 6.3% greater for the 2-yr system than for the 3-yr system (Table 7). Without subsidies, returns for corn in the 3- and 4-yr systems were greater than for corn in the 2-yr system, and the same pattern occurred for soybean (Table 7). Returns for alfalfa in 4-yr system exceeded returns for both corn and soybean in the 2-yr system.

The addition of subsidy payments changed the magnitude of differences among the cropping systems in returns to land and management, although it did not change the rank order of the systems. With subsidies, returns from the 4-yr system were only 1.1% greater than from the 2-yr system (Table 7). In contrast, subsidies increased the advantage in returns of the 2-yr system to 7.9% over the 3-yr system (Table 7). These patterns reflected differential rates of subsidization among crop rotation systems. The gain in net returns due to subsidies was 27% for the 2-yr system, 25% for the 3-yr system, and 20% for the 4-yr system (Table 7).

DISCUSSION

Our results show that corn and soybean yields in LEI systems can be sustained at levels that match or exceed levels obtained from conventional systems during the initial years following conversion from conventional management practices (Table 5), despite large reductions in agrichemical use (Fig. 1A and 1B). The frequency of corn and soybean phases within the diversified LEI systems examined in this study was lower than in the conventional 2-yr rotation system, so total corn and soybean production over time would be lower in the LEI systems. Nonetheless, the additional crops used within the LEI systems can have substantial value in the marketplace (Table 7), or play key roles in the nutrition of livestock in mixed farming operations.

Reductions in reliance on synthetic N fertilizer in the LEI systems were made possible by biological N_2 fixation by forage legumes and applications of nutrients within manure (Table 2). Although we did not quantify N_2 fixation and N release by forage legumes in this study, Heichel et al. (1984, 1985) found that first-year stands of red clover fixed 133 kg N ha^{-1} yr^{-1} and established stands of alfalfa fixed 114 to 224 kg N ha^{-1} yr^{-1}. Fox and Piekielek (1988) estimated that residues of red clover and alfalfa provided the equivalent of 96 and 121 kg N ha^{-1}, respectively, of synthetic fertilizer to corn grown in the year following termination of the legume stands.

We estimate that the quantities of N applied in manure in this study were about 70% of what could be used on a mixed crop-livestock farm where cattle were fed with the amounts of corn and forage produced in our experimental plots (I-FARM, 2007). Manuring has been shown to increase corn and soybean yields, even when the nutrient requirements of those crops are met with other fertility sources (Magdoff and Amadon, 1980; Eghball and Power 1999; McAndrews et al., 2006). Yield enhancement by manure and other organic amendments has been attributed to changes in soil biological, physical, and chemical properties (Weil and Magdoff, 2004).

Increasing crop diversity and rotation length may have contributed to higher soybean yields in the 3- and 4-yr systems compared with the 2-yr system. Summarizing the results of several long-term rotation experiments, Porter et al. (1997) concluded that maximum corn yields could be achieved in a 2-yr corn–soybean rotation, but that a longer rotation with lower soybean frequency was needed to maximize soybean yield. Similarly, Mallarino et al. (2006) noted that over a 21-yr period, no yield difference occurred for corn when the crop was grown at high N fertilizer levels in a 2-yr rotation with soybean vs. when it was grown in a 4-yr rotation sequence of corn/oat/alfalfa/alfalfa. In contrast, soybean yield was higher when that crop was grown in a 4-yr rotation (soybean/corn/oat/corn) than in a 2-yr rotation with corn.

We believe it is unlikely that the yield differences observed in 2005 and 2006 between the LEI 3-yr and 4-yr systems and the conventional 2-yr system resulted from nutrient insufficiency in the conventional system, since soil tests indicated optimum to high levels of N, P, and K in all systems. Nitrogen fertilizer rates applied to corn in the 2-yr system of the present study were similar to rates that maximized yield of corn rotated with soybean during 2000 to 2004 in central Iowa (Sawyer et al., 2006). It is possible that other nutrients added through manure applications, especially P and K, may have provided a yield response for corn and soybean in the LEI systems. We did not, however, create subplots for nutrient manipulations within our experiment to determine whether ambient fertility levels limited or promoted yields. Yield gains due to changes in rotation length and crop sequence under conditions of high soil fertility and adequate pest suppression have been attributed to microbiological, biochemical, and

Table 7. Gross revenues, production costs, labor requirements, and returns to land and management for contrasting rotation systems, 2003 to 2006.

Rotation	Gross revenue†	Production cost‡	Labor requirement	Return to land and management, no subsidies§	Return to land and management, with subsidies¶
	$ ha^{-1} yr^{-1}		h ha^{-1} yr^{-1}	$ ha^{-1} yr^{-1}	
2-yr rotation					
Corn	1202.05	582.48	1.61	603.52	793.96
Soybean	757.18	331.99	2.03	405.01	489.83
Rotation avg.	979.62	457.24	1.82	504.27	641.90
3-yr rotation					
Corn	1238.63	500.42	4.25	695.68	895.57
Soybean	816.34	291.61	2.52	499.61	585.71
Small grain/clover	499.29	251.99	1.90	228.28	303.29
Rotation avg.	851.42	348.01	2.89	474.52	594.85
4-yr rotation					
Corn	1250.41	483.97	4.27	723.73	924.15
Soybean	824.12	292.63	2.52	506.35	592.65
Small grain/alfalfa	613.80	350.44	2.67	236.65	311.64
Alfalfa	929.04	194.27	4.17	693.10	768.10
Rotation avg.	904.34	330.33	3.41	539.96	649.14

† Crop prices used in the calculations were $95.70 Mg^{-1} for corn; $227.85 Mg^{-1} for soybean; $82.45 Mg^{-1} for triticale grain; $110.25 Mg^{-1} for oat grain; $54.45 Mg^{-1} for triticale and oat straw; and $77.10 Mg^{-1} for alfalfa hay.

‡ Costs included field operations, handling, and hauling, and for corn, drying as well. Land and labor costs were not included.

§ Labor charge was set at $10 h^{-1}.

¶ Crop subsidies comprised loan deficiency, counter cyclical, and direct payments.

physical factors, but the relevant mechanisms remain incompletely understood (Crookston et al., 1991; Bullock, 1992).

Although not quantified in this study, potential environmental impacts of LEI systems should be considered. Magdoff et al. (1997) and Dinnes et al. (2002) indicated that reductions in synthetic N fertilizer use, coupled with greater use of perennial crops and judicious use of manure, constitute important components of strategies to conserve N and protect water from N contamination. Data from the study by Drinkwater et al. (1998) indicate that a diversified cropping system, which included small grains and forage legumes in addition to corn and soybean, and which received manure, but no synthetic N, lost less nitrate N through leaching than did a conventionally managed corn/soybean system. We suggest that greater use of LEI systems similar to those used in the present study may offer substantial opportunities to produce adequate crop yields while improving N management.

Gilliom et al. (2006) noted that reducing herbicide use is likely to be an effective way to reduce herbicide concentrations in the hydrologic system. Results of the present study indicate that major reductions in herbicide use can be achieved in diversified LEI systems without compromising weed suppression, at least during the initial years following conversion from conventional management. By the fourth year of this study (2006), total herbicide use in corn and soybean was 94% lower in the 3- and 4-yr systems compared with the conventional 2-yr system (Table 3), yet only trivial amounts of weed biomass ($\leq$0.8 g m^{-2}) were measured in corn and soybean in any of the systems (Table 6). Continued monitoring of weed dynamics in our study plots over several more rotation cycles would allow for determination of whether effective weed suppression could be maintained with low levels of herbicides for extended periods.

The numbers of giant foxtail and velvetleaf seeds we added to our manipulated subplots in 2002 were within the range of seed shed rates observed by other investigators in corn and soybean fields (Cardina and Norquay, 1997; Forcella et al., 2000; Bussan et al., 2000, 2001). Following this initial experimental pulse of seeds, giant foxtail and velvetleaf seed bank densities declined or remained stable over the subsequent 4 yr in all of the rotation systems (Fig. 2A and 2B), despite greater seed production in the 3- and 4-yr systems than in the 2-yr system (Heggenstaller and Liebman, 2006). Modeling analyses conducted by Westerman et al. (2005) indicated that the LEI 4-yr rotation system could provide effective control of velvetleaf and other weeds with similar life history characteristics due to the diversity of stress and mortality factors the rotation imposed on the weeds. Seed losses to rodent and insect seed predators occurred in all three systems (Heggenstaller et al., 2006; O'Rourke et al., 2006), but this ecological interaction appears to have been particularly important for suppressing weed densities in the LEI systems (Davis and Liebman, 2003; Davis et al., 2003; Westerman et al., 2005).

Although weed suppression was largely effective in all of the systems included in this study, certain aspects of the LEI systems require more attention. Weed growth in the stubble of small grains intercropped with alfalfa in the 4-yr system was problematic in 2003 (Table 7), when dry conditions in August (Table 4) precluded a fall alfalfa harvest, but not in other years, when weeds were removed with hay harvested in September. In contrast, weeds were more frequently a problem in the stubble of small grains intercropped with red clover in the 3-yr system (Table 6), which was not removed as hay in late summer. In a study of weed dynamics on a commercial farm using a diversified LEI system similar to the 4-yr rotation reported about here, Buhler et al. (2001) observed increased weed survival and seed production in small grain stubble and a newly established legume underseeding as compared to other phases of the rotation. Norris and Ayres (1991) reported that suppression of yellow foxtail [*Setaria glauca* (L.) Beauv.] in alfalfa could be improved by adjusting harvest timing. We suggest that analogous improvements in weed suppression in small grain stubble might be accomplished by timely late summer mowing.

The rotation systems and management practices used in the present study were well suited to investigations of crop performance and weed dynamics, but should not be construed to represent economically optimum systems. For example, in the case of LEI systems, longer rotations with additional years of hay might be more profitable; for conventional systems, different herbicide products might be more cost-effective. The present study also did not consider the economic impacts of integrating crop and livestock enterprises. Despite these shortcomings, the systems evaluated in this study indicate the types of outcomes that might be achieved with conventional and diversified LEI systems for agronomic crops in the midwestern United States.

One of the key points to emerge from the present study is that productive and profitable LEI cropping systems are based on optimizing overall system performance by fitting together individual crop components. For example, though triticale and oat added relatively little revenue themselves to the 4-yr rotation system (Table 7), they served as effective nurse crops for establishing alfalfa, thereby minimizing erosion, suppressing velvetleaf growth without herbicides (Heggenstaller and Liebman, 2006), and providing habitat for seed predators attacking velvetleaf and giant foxtail seeds (Heggenstaller et al., 2006). Alfalfa was less profitable than corn (Table 7), but its inclusion within the rotation system allowed significant reductions in N use for corn (Table 2), while also suppressing velvetleaf seed production (Heggenstaller and Liebman, 2006) and fostering weed seed predators (Heggenstaller et al., 2006). In coming years, if society seeks to satisfy multiple performance criteria for agriculture, including enhanced crop productivity, satisfactory profitability, and improved environmental protection through reduced agrichemical use, continued attention to the design and performance characteristics of LEI systems will be required.

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